

Precursors see inside black holes

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Abstract

We argue that, given the nonlocal nature of precursors in AdS/CFT correspondence, the boundary field theory contains information about events inside a black hole horizon. The essence of our proposal is sketched in figure 1, and relies on the global nature of event horizons.

August, 2002

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1. Introduction

With the pressing problems related to string theory in cosmological settings, there has been a resurgence of interest in physics associated with interiors of black holes. So far, the best handle we have appears in the context of the AdS/CFT correspondence [1,2,3,4], where string theory on AdS (which is a gravitational theory, and can contain black holes) has a dual description in terms of a field theory “living on the boundary”. The details of the correspondence remain yet to be unraveled, and its causal properties to be better understood; nevertheless, there are certain expectations on how the bulk information is to be holographically encoded on the boundary.

One system in which we can try to ask these questions is the large Schwarzschild black hole in $AdS_5 \times S^5$. This is well known to correspond to an approximately thermal state in the gauge theory. The spacetime has an event horizon, i.e. the black hole interior is causally disconnected from the boundary. One may then ask: *Is the physics inside the event horizon encoded by the boundary theory?* Affirmative answer immediately leads to the more ambitious question¹: *How?* Once this is understood, one may hope to come closer to the resolution of the black hole information paradox, as well as to get a better handle on the singularity inside the horizon. While these are certainly worthy—and rather lofty—goals by themselves, a better understanding and “resolution” of spacelike singularities would provide a new window into studying cosmological singularities in string theory.

In this brief note, we point out that under the commonly-accepted assumption of precursors, at least part of the spacetime inside the horizon will be accessible to the field theory. In the following we will explain this idea in more detail, using a simple gedanken experiment which exemplifies it. No explicit calculations are presented, since it is the matter-of-principle point that we wish to stress.

2. Gedanken experiment

Let us, for the moment, consider pure AdS, without any black hole present. Even certain local boundary operators contain a remarkable amount of information about static

¹ Such questions have been considered previously [5,6,7,8], but despite extensive work, these issues still remain somewhat obscure. The holographic representation of horizons in terms of the dual gauge theory has also been discussed [9,10,11,12,13]; we believe that the lack of complete success in this venue stems largely from the global nature of the horizon.

objects deep inside the bulk of AdS [14]; but since such operators are determined only from the asymptotic values of the bulk fields, any dynamical information is propagated out in a manner consistent with bulk causality. In particular, no local operators on the boundary can see events inside a causally disconnected region, such as a black hole. However, as has been argued [15,16,17], an event in the bulk is actually encoded by *nonlocal* operators on the boundary, with the associated scale dictated by the UV/IR correspondence [18,19]. A concrete proposal has been put forth that such operators are decorated Wilson loops. While this has not yet been proved², the essential point is the existence of *some* set of nonlocal operators encoding the bulk, apparently “instantaneously”, i.e. before any message sent from the event could reach the boundary.

If we accept this assumption, the fact that the boundary field theory must also contain some information about physics inside a horizon follows almost immediately. (A similar observation has been made recently in [7], but their attempts at exemplifying the process through “flossing the black hole” cast some doubt on the possibility of extracting information from inside the horizon. Here we suggest a much simpler process, which does not rely on inconclusive tree level computations.) The event horizon is a global object, defined as the boundary of the past of the future infinity, which means that we cannot determine the presence or position of the event horizon until we know the entire future evolution of the spacetime. In particular, an innocent-looking, empty, locally AdS part of spacetime can in fact be an interior of a black hole, if later there forms a large enough black hole for its horizon to stretch far enough into the past to encompass the event in question.

Taking advantage of this fact, we can consider the following gedanken experiment: Start with “empty” AdS space, and consider some event, labeled p in Fig.1a. As a boundary observer, one can obtain instantaneous information about the event p , for instance by measuring³ appropriately decorated Wilson loop W . *After* this measurement has been made, i.e. entirely to the future of W , one can send in a shell s of radiation with sufficient energy such that when it implodes in the center of AdS, it forms a large black hole, as

² The identification of precursors with Wilson loops has been suggested in [15] and expanded in [16]; while the latter’s calculation was challenged by [7], further analysis [17] suggested that the precursor information is coded in high frequency components of Wilson loops, or the so-called decorated Wilson loops.

³ While it was argued [20] that a Wilson loop cannot be measured in the conventional non-demolition sense, it can be measured in a suitable demolition experiment, such as sketched out in [17], which is all we need for the present argument.

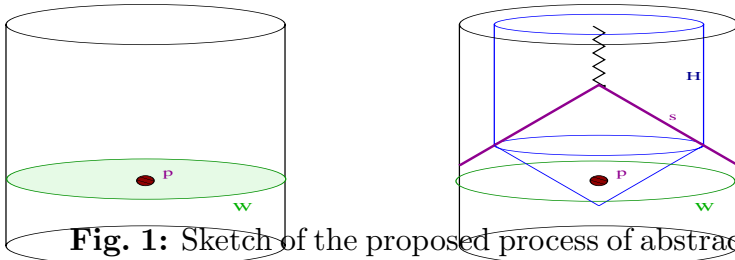


Fig. 1: Sketch of the proposed process of abstracting information from inside of the horizon: a) An event p , in locally pure AdS space is measured by W . b) After this measurement is performed, a shell s collapses, forming a black hole with a horizon H which encompasses p .

sketched in Fig.1b. If the shell is spherically symmetric, the spacetime everywhere outside this shell will be that of Schwarzschild- $AdS_5 \times S^5$, whereas inside the shell the spacetime is described by pure $AdS_5 \times S^5$. The global event horizon for this spacetime will be obtained by tracing back the radially outgoing null rays, denoted by H in Fig.1b. As apparent from Fig.1, these can originate at the center of AdS prior to p . In particular, provided the shell is sent in within time of order the AdS radius, one can always make the resulting black hole large enough for its horizon to encompass the event p .

This implies that one has in fact succeeded in “measuring” an event, p , which is inside a black hole horizon. This is seen more clearly from the corresponding Penrose diagram, Fig.2.

3. Discussion

Several comments about this process are in order. First, while we claim that, through precursors, the boundary field theory encodes some information about events in the interior

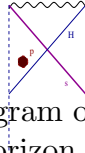


Fig. 2: Penrose diagram of the proposed process of abstracting information from inside of the horizon corresponding to the sketch in Fig.1b.

of black holes, our claim does not imply violations of causality. This is simply because the “measurement”, W , is not local. No message is being sent between any two spacelike-separated points. Correspondingly, one might then object that 1) a local field theory observer can’t set up the collapse of the shell fast enough if he waits till after W to decide whether to collapse the shell or not, and 2) a single local observer cannot get any information out of the nonlocal operator W before the shell is to be sent in. Both of these statements are true, but they do not contradict the claim that there is some quantity, W , which encodes some information about p , and yet is unaffected (due to the causality of the local quantum field theory on the boundary) by the eventual creation of the horizon. In fact, this is suggestive of the generic expectation that extracting information out of black holes must necessarily involve some nonlocal physics.

Another objection that one might raise concerns the sudden creation of the shell’s energy, i.e. that there is a source introduced on the boundary. This however does not refute the basic point that p can be measured despite being inside the horizon. One may alternately set up the experiment with the shell’s energy being present for all time, as long as the shell implodes and creates a black hole when required. We have been talking about a “shell” without specifying how it is to be constructed from string theory, because such detailed information is also irrelevant to the basic point. One can in fact consider more complicated nonspherical geometries, such as several colliding gravitational shock waves,

which may nevertheless be easier to discuss in the dual field theory [21].

Clearly, for obtaining a specific demonstration of extracting information from a black hole, we would first need to specify exactly all the components in our set-up before any explicit calculation could be carried out. So far, the main obstacle to verifying our claim by an explicit computation is the incomplete understanding of the holographic encoding of the bulk, namely the exact nature of W . A possible simplification is to work in lower dimensions where exact solutions are easier to find, such as in $AdS_3 \times S^3 \times T^4$; however, even in this context, sufficient understanding of the precursors has not yet been achieved.

It is not clear from our construction how much information one can actually extract out of the black hole, and what part of the spacetime inside the black hole can one extract information about. In the above example, we claimed that we can learn something about the part of spacetime to the past of the shell, since there the picture is the same as for pure AdS. In terms of Fig.2, our process can access the left wedge, but it is less clear whether we can similarly extract any information from the top wedge. Since the left wedge is still far from the singularity, one might worry that our proposal cannot hope address the motivation of resolving the singularity. This does not appear to be a fundamental obstacle, since one may hope to get closer to the singularity by considering different types of collapse.

In summary, we are still faced with the outstanding question of whether or not the gauge theory can probe physics inside the event horizon. Since this region is causally disconnected from the boundary, one may fear that the existence of the horizon will prevent the gauge theory from “seeing” what goes on behind it, as is true for the local operators. In this note we have shown that, given the existence of precursors, which are nonlocal operators, one can find situations in which the boundary theory does know about events behind the horizon. While our gedanken experiment does not address extracting any information from an existing black hole, it demonstrates the important point that the causal properties of the horizon do not pose a fundamental obstacle to learning something about the physics behind it. Once this crucial causal obstacle is removed, extracting *all* information out of black holes may seem more hopeful.

Acknowledgements

I would like to thank Lenny Susskind and Steve Shenker for encouraging me to write-up the idea, and Gary Horowitz for initial discussions. This work was supported by NSF Grant PHY-9870115.

References

- [1] J. Maldacena, *The Large N Limit of Superconformal Field Theories and Supergravity*, Adv. Theor. Math. Phys. 2 (1998) 231, hep-th/9711200.
- [2] E. Witten, *Anti De Sitter Space And Holography*, Adv. Theor. Math. Phys. 2 (1998) 253, hep-th/9802150.
- [3] S. Gubser, I. Klebanov, and A. Polyakov, *Gauge Theory Correlators from Non-Critical String Theory*, Phys. Lett. B428 (1998) 105, hep-th/9802109.
- [4] O. Aharony, S.S. Gubser, J. Maldacena, H. Ooguri, Y. Oz, *Large N Field Theories, String Theory and Gravity*, Phys. Rept. 323 (2000) 183, hep-th/9905111.
- [5] V. Balasubramanian and S. F. Ross, *Holographic Particle Detection*, Phys. Rev. D61 (2000) 044007, hep-th/9906226
- [6] J. Louko, D. Marolf, and S. F. Ross, *On geodesic propagators and black hole holography*, Phys.Rev. D62 (2000) 044041, hep-th/0002111.
- [7] S. B. Giddings and M. Lippert, *Precursors, black holes, and a locality bound*, Phys. Rev. D 65, 024006 (2002), hep-th/0103231.
- [8] J. M. Maldacena, *Eternal black holes in Anti-de-Sitter*, hep-th/0106112.
- [9] T. Banks, M. R. Douglas, G. T. Horowitz and E. J. Martinec, *AdS dynamics from conformal field theory*, hep-th/9808016.
- [10] V. Balasubramanian, P. Kraus, A. E. Lawrence and S. P. Trivedi, *Holographic probes of anti-de Sitter space-times*, Phys. Rev. D 59, 104021 (1999), hep-th/9808017.
- [11] D. Kabat and G. Lifschytz, *Gauge theory origins of supergravity causal structure*, JHEP 9905, 005 (1999), hep-th/9902073.
- [12] U. H. Danielsson, E. Keski-Vakkuri and M. Kruczenski, *Black hole formation in AdS and thermalization on the boundary*, JHEP 0002, 039 (2000) hep-th/9912209.
- [13] J. P. Gregory and S. F. Ross, *Looking for event horizons using UV/IR relations*, Phys. Rev. D 63, 104023 (2001), hep-th/0012135.
- [14] G. T. Horowitz and V. E. Hubeny, *CFT description of small objects in AdS*, JHEP 0010, 027 (2000), hep-th/0009051.
- [15] J. Polchinski, L. Susskind, and N. Toumbas, *Negative Energy, Superluminosity and Holography*, Phys.Rev. D60 (1999) 084006, hep-th/990322.
- [16] L. Susskind and N. Toumbas, *Wilson Loops as Precursors*, Phys.Rev. D61 (2000) 044001, hep-th/9909013 .
- [17] B. Freivogel, S. B. Giddings and M. Lippert, *Toward a theory of precursors*, hep-th/0207083.
- [18] L. Susskind and E. Witten, *The Holographic Bound in Anti-de Sitter Space*, hep-th/9805114.
- [19] A. Peet and J. Polchinski, *UV/IR Relations in AdS Dynamics*, Phys. Rev. D59 (1999) 065011, hep-th/9809022.

- [20] D. Beckman, D. Gottesman, A. Kitaev and J. Preskill, *Measurability of Wilson loop operators*, Phys. Rev. D 65, 065022 (2002), hep-th/0110205.
- [21] G. Horowitz and N. Itzhaki, *Black Holes, Shock Waves, and Causality in the AdS/CFT Correspondence*, JHEP 9902 (1999) 010, hep-th/9901012